Advances in NAIRAS Atmospheric and Space Radiation Nowcast and Forecast

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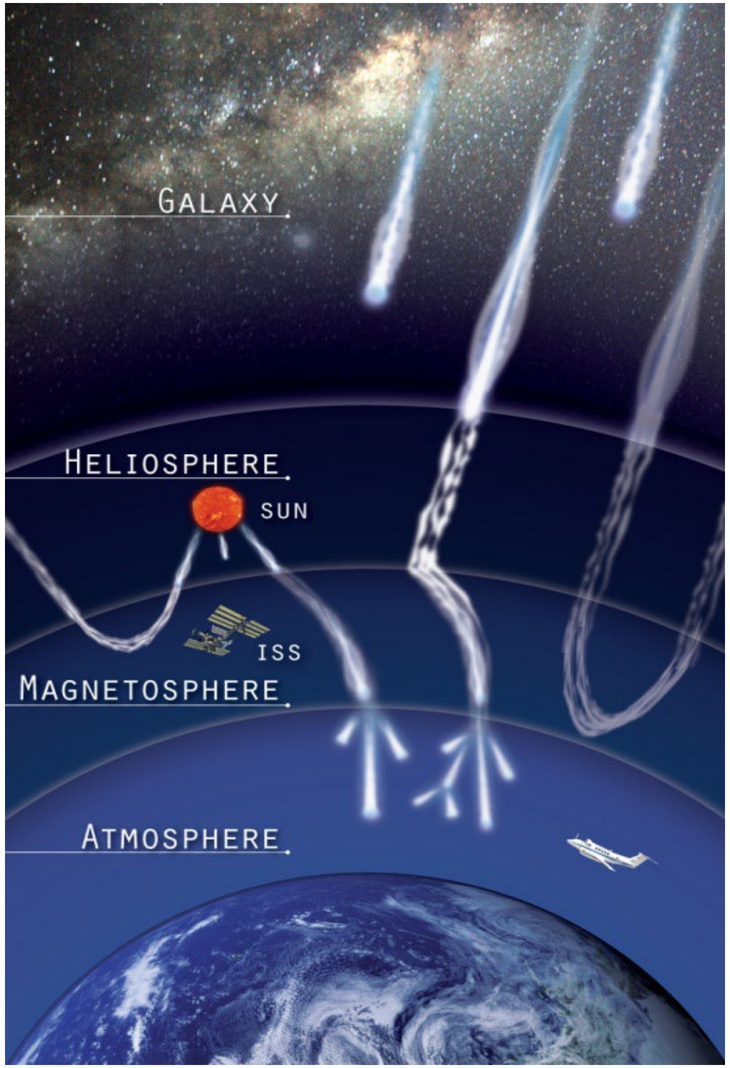
NAIRAS Model

- **Nowcast of Aerospace Ionizing RAdiation System (NAIRAS) Model**
  - Running in real-time on NASA computer cluster since 2011, aviation radiation results hosted publicly on Space Environment Technologies server/website
  - Running in real-time at Community Coordinated Modeling Center (CCMC) since 2020
- **Key (Vintage) Model Features**
  - Physics-based **HZETRN** (High Charge (Z) and Energy TRaNsport) code
  - Real-time inclusion of solar energetic particle (**SEP**) radiation
  - Real-time solar-magnetospheric effects on radiation (cutoff model *by Kress et al.* [*2004, 2010*])
- **New/Current Model Developments**
  - Extend from atmosphere to space environment, now including trapped protons (**TRP**)
  - SEP heavy-ions (Z=2-92, A=4-238) added
  - Single-Event Effects (**SEE**) radiation risk assessment quantities added
  - Run-on-Request (**RoR**) @ CCMC

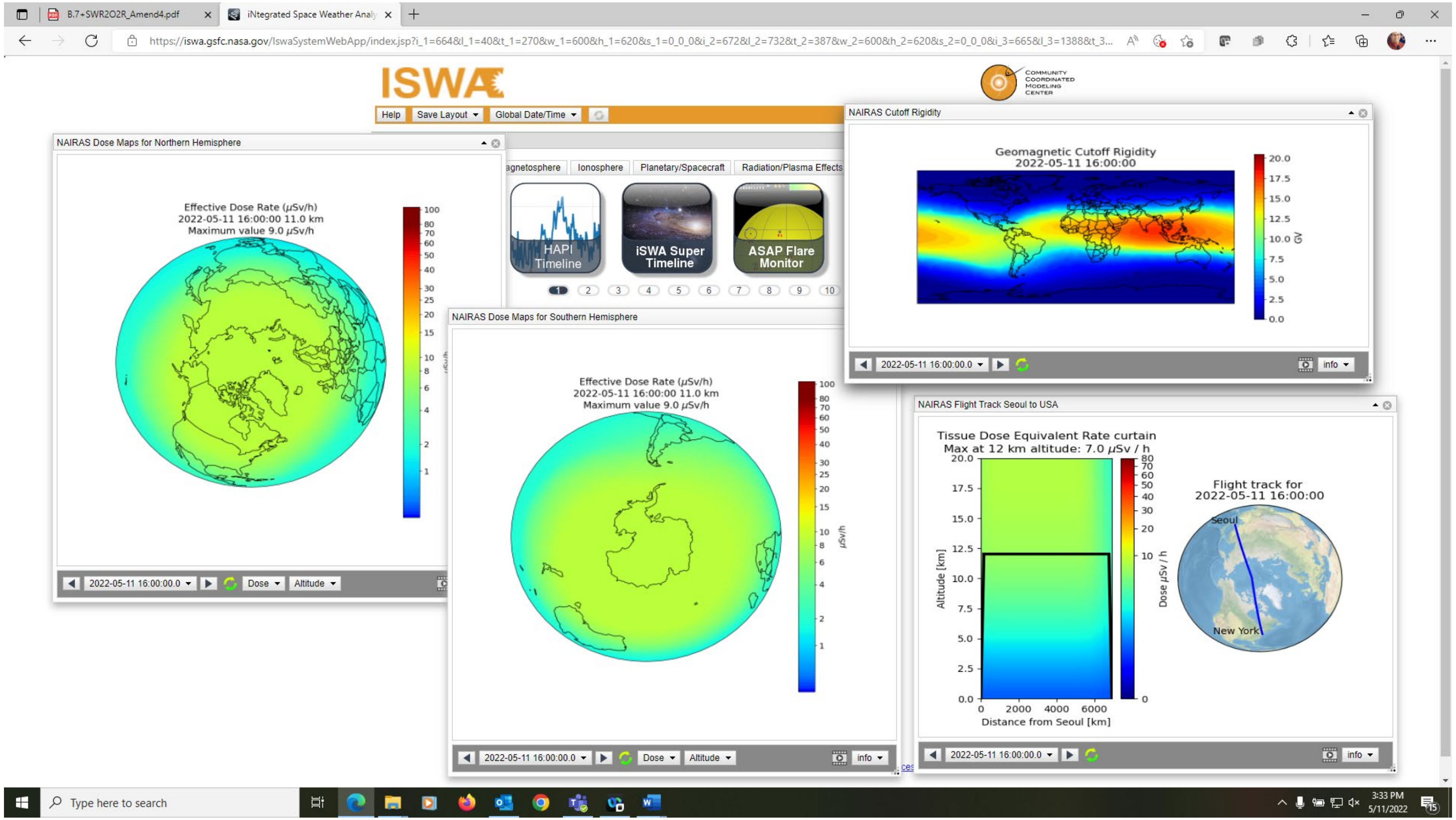


Outline

- **NAIRAS Real-Time Interface @ CCMC (publicly available)**
- **NAIRAS RoR Capability @ CCMC (publicly available)**
- **NAIRAS Validation Studies in the Atmosphere**
- **NAIRAS Predictions and Validation of Space Radiation**
- **Summary and Conclusions**

Real-Time NAIRAS @ CCMC

CCMC Integrated Space Weather Analysis (iSWA) System



NAIRAS Run-on-Request (RoR) User Input

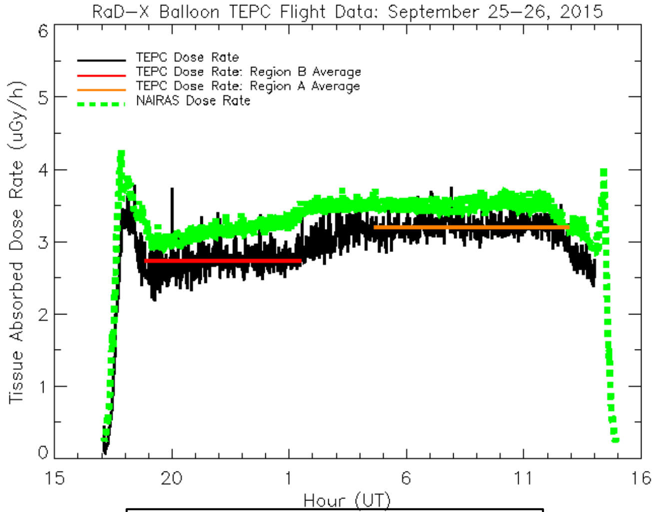
Table: RoR Capability Summary and Description

Run Option	Output Quantities		User Input
Global Dosimetric	Absorbed dose in silicon, absorbed dose in tissue, dose equivalent, ambient dose equivalent, effective dose		Start/End Date-Time
Flight Trajectory	Dosimetric & Flux/Fluence		Trajectory file
	Dosimetric	Same as global run	Shielding depths for dosimetric calculations
	Flux/Fluence		Shielding depths for flux/fluence calculations
		Integral • GCR/SEP LET (linear energy transfer) • SEP proton • TRP proton • TRP electron	Lower LET/energy bounds of integral quantity
		Differential • GCR/SEP/TRP LET (linear energy transfer) • SEP proton • TRP proton • TRP electron	N/A (full model differential spectra written to output)

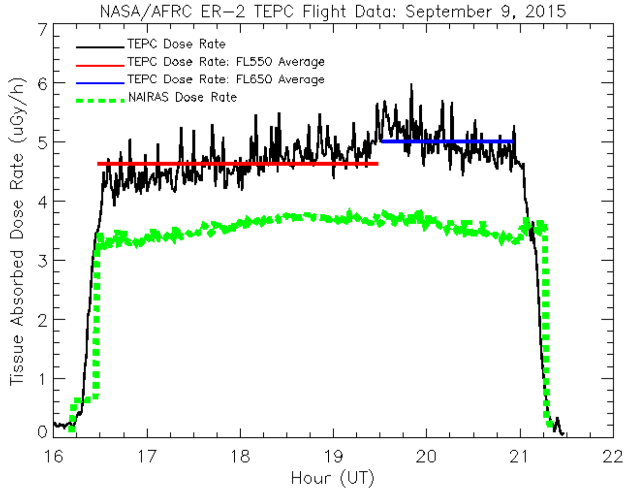
Red: In Progress

NAIRAS Validation @ 0-40 km

RaD-X Region A: 21 km < Z < 27 km; Region B: Z >32.5 km

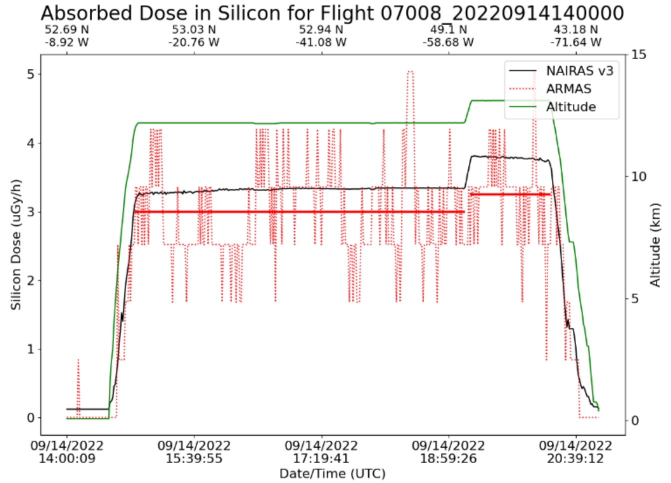


RaD-X ER-2: Z = 17km, 20km

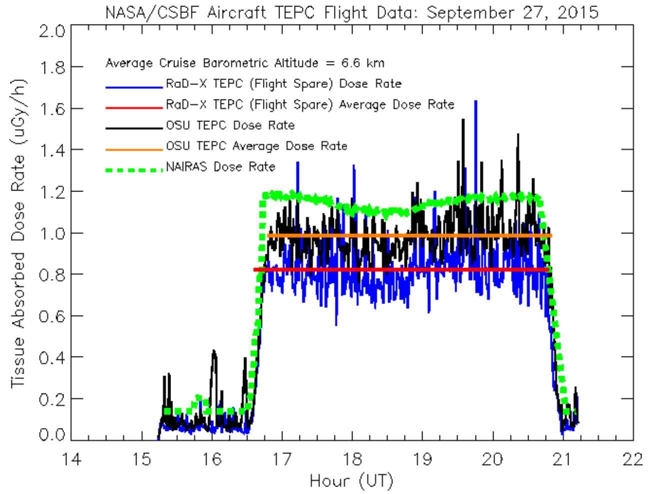


- **Legend**
  - NASA Radiation Dosimetry Experiment (RaD-X)
  - Automated Radiation Measurements for Aerospace Safety (ARMAS) semiconductor dosimeter
  - Columbia Scientific Balloon Facility (CSBF)
  - Tissue equivalent proportional counter (TEPC)
- **Absorbed dose rate comparisons**
  - Tissue (top left, bottom left, bottom right)
  - Silicon (top right)
  - **Agreement within 30%**

US Corporate Aircraft: EINN-KBDL



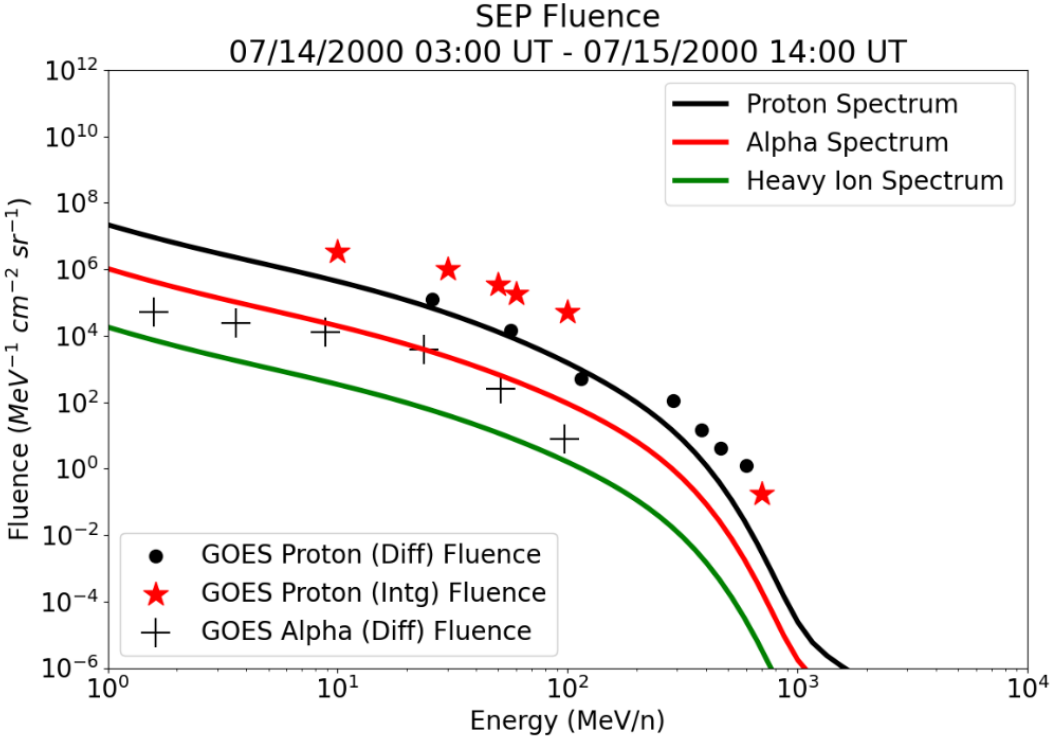
RaD-X CSBF Chase Plane: Z = 6.6 km



NAIRAS SEP Spectral Fitting

- **Protons**
  - Fit spectrum to GOES integral proton flux
  - Fit four functional forms
  - Choose solution with minimum chi-square
- **Alpha**
  - Retain proton spectral shape from previous step
  - Scale proton spectrum by optimal normalization factor using GOES alpha differential flux
- **Heavy-Ion (Z > 2)**
  - Scale alpha spectrum from previous step using element/alpha abundance ratios
  - *Major heavy-ion abundance ratios*: using GOES alpha and ACE Solar Isotope Spectrometer (SIS) element flux measurements (Xapsos et al., 2007)
  - *Minor heavy-ion abundance ratios*: using ACE/SIS and International Sun-Earth Explorer-3 (ISEE-3) element flux measurements (Reames, 1998)
  - *Remaining heavy-ion abundance ratios*: using photospheric emission measurements with a scale factor of 4 if the first ionizing potential is less than 10 eV (Grevesse, 2019)

Bastille Day SEP Event Fluence



SEP proton spectrum fit to GOES integral proton flux. GOES differential proton flux shown for comparison.

SEP spectra fit to GOES 5-min data. Fluence is 5-min fitted-spectra summed over event.

SEP Heavy-Ion Effective Dose in LEO

LEO Trajectory: Inclination 51.6-degree, 450 km

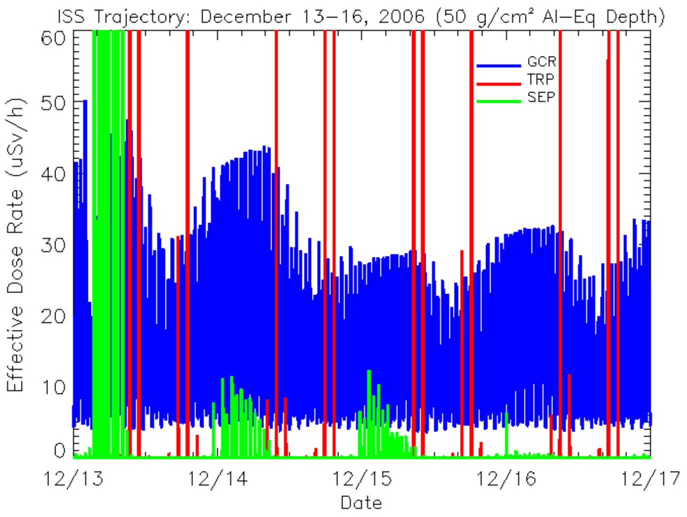
SEP Event Date	Start Time (UT)	Duration (Hours)	Shielding Depth: 2 g/cm^2		Shielding Depth: 50 g/cm^2	
			Total Effective Dose (mSv)	Total Effective Dose Ratio (heavy/proton)	Total Effective Dose (mSv)	Total Effective Dose Ratio (heavy/proton)
10/19/1989	12:00	48	40.4	2.02	0.20	1.16
07/14/2000	**09:00**	**48**	**168.0**	**2.33**	**1.52**	**1.52**
11/08/2000	22:00	24	158.2	2.10	1.05	1.34
09/29/1989	09:00	48	23.4	2.59	0.08	1.28
10/28/2003	**10:00**	**48**	**140.3**	**2.73**	**0.96**	**1.52**
11/04/2001	16:00	48	173.0	1.70	1.18	1.21
01/20/2005	**06:00**	**24**	**17.7**	**1.84**	**0.04**	**1.42**
03/07/2012	**01:00**	**48**	**52.3**	**2.04**	**0.06**	**1.37**
04/15/2001	**13:00**	**48**	**4.7**	**1.90**	**0.14**	**1.53**
08/12/1989	14:00	48	17.3	1.66	0.01	1.20

Event Selection: 10 largest SEP events with respect to free-space event dose (Minow et al., Space weather architecture options to support human and robotic deep space exploration, NASA Langley Research Center, Hampton, VA, USA, Tech. Mem. TM/2020-5000837, Apr. 2020.)

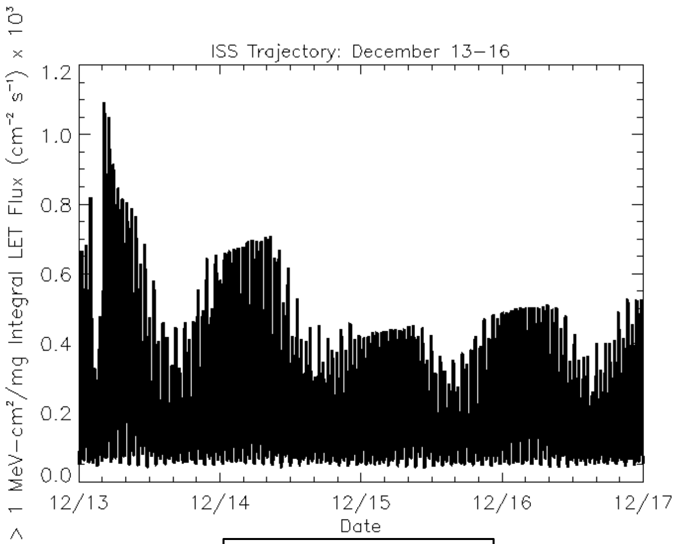
Take Away 1: 5 of 10 events SEP heavy-ions increase effective dose by ~40% (**blue**) to ~50% (**red**) at 50 g/cm^2

Take Away 2: Nearly all events SEP heavy-ions increase effective dose by factor 2-3 at 2 g/cm^2 (EVA)

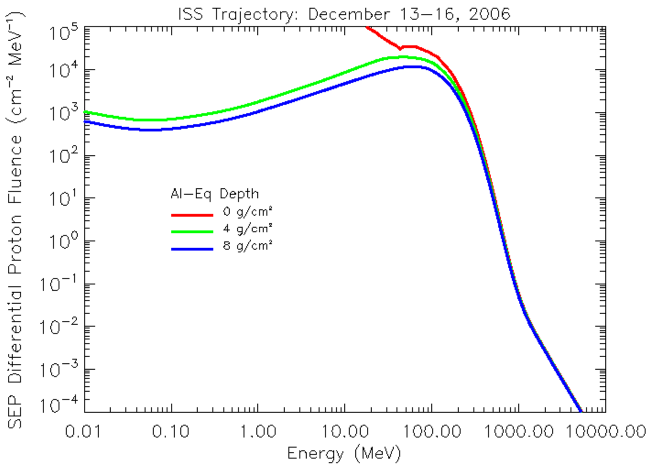
Dec 2006 SEP Events: ISS Radiation

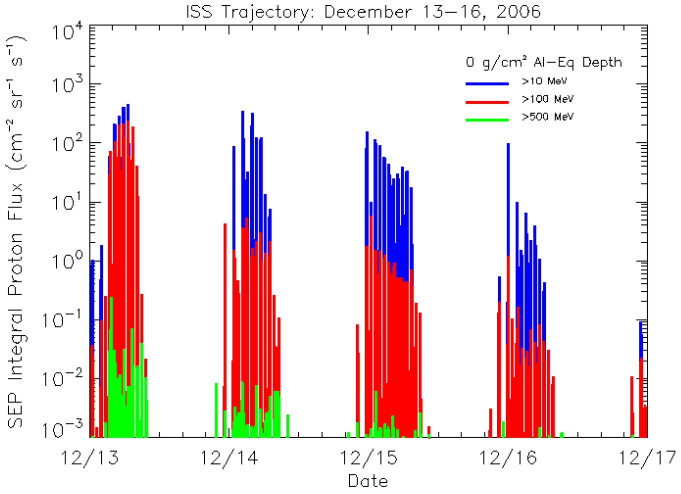


Al Shielding: 50 g/cm²



Al Shielding: 4 g/cm²



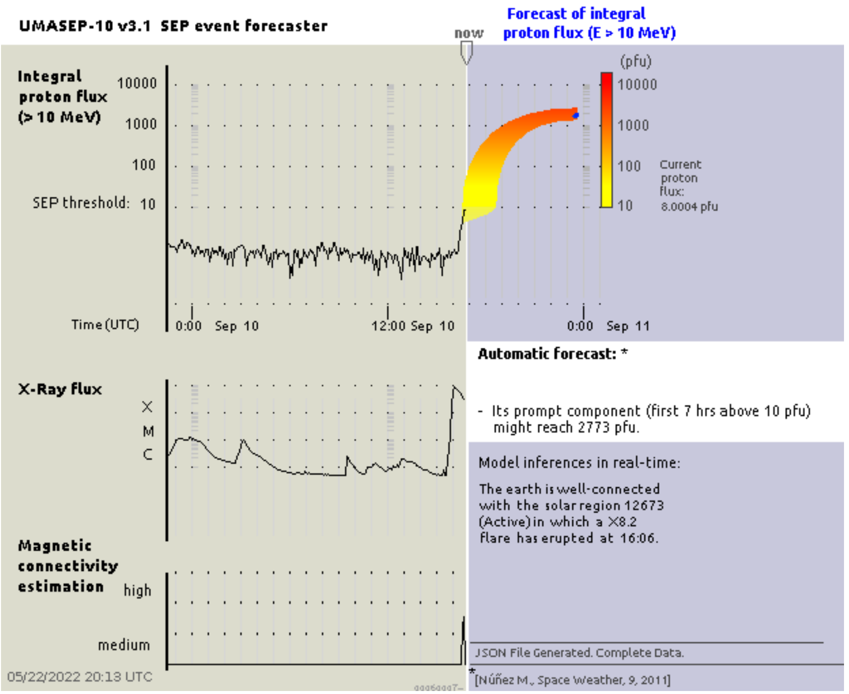


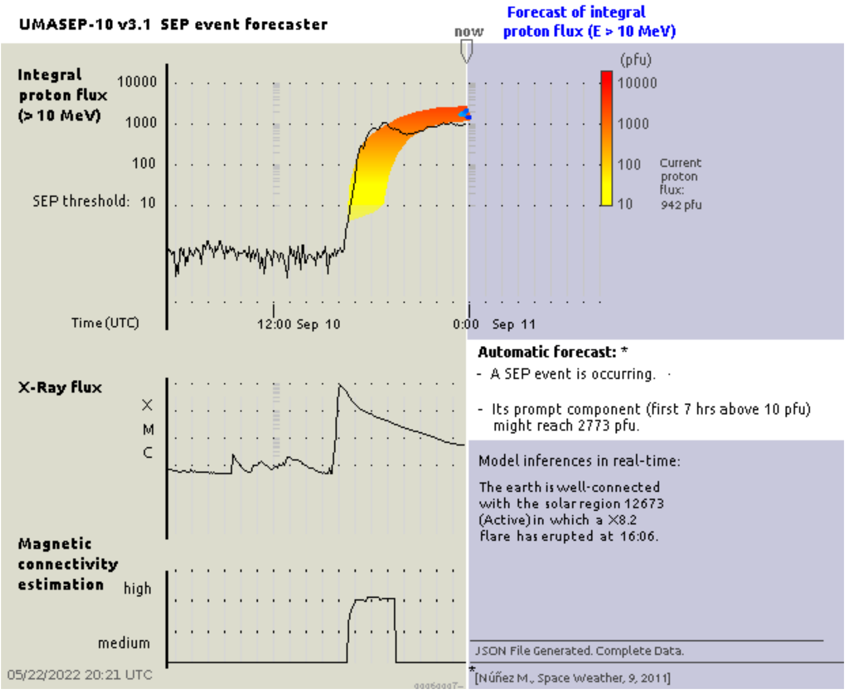
UMASEP Forecast: September 2017

Example Below: >10 MeV Peak Integral Proton Flux

Forecast Issue Time 09/10/2017 16:40 UT

Forecast Window: Issue Time + 7 hours

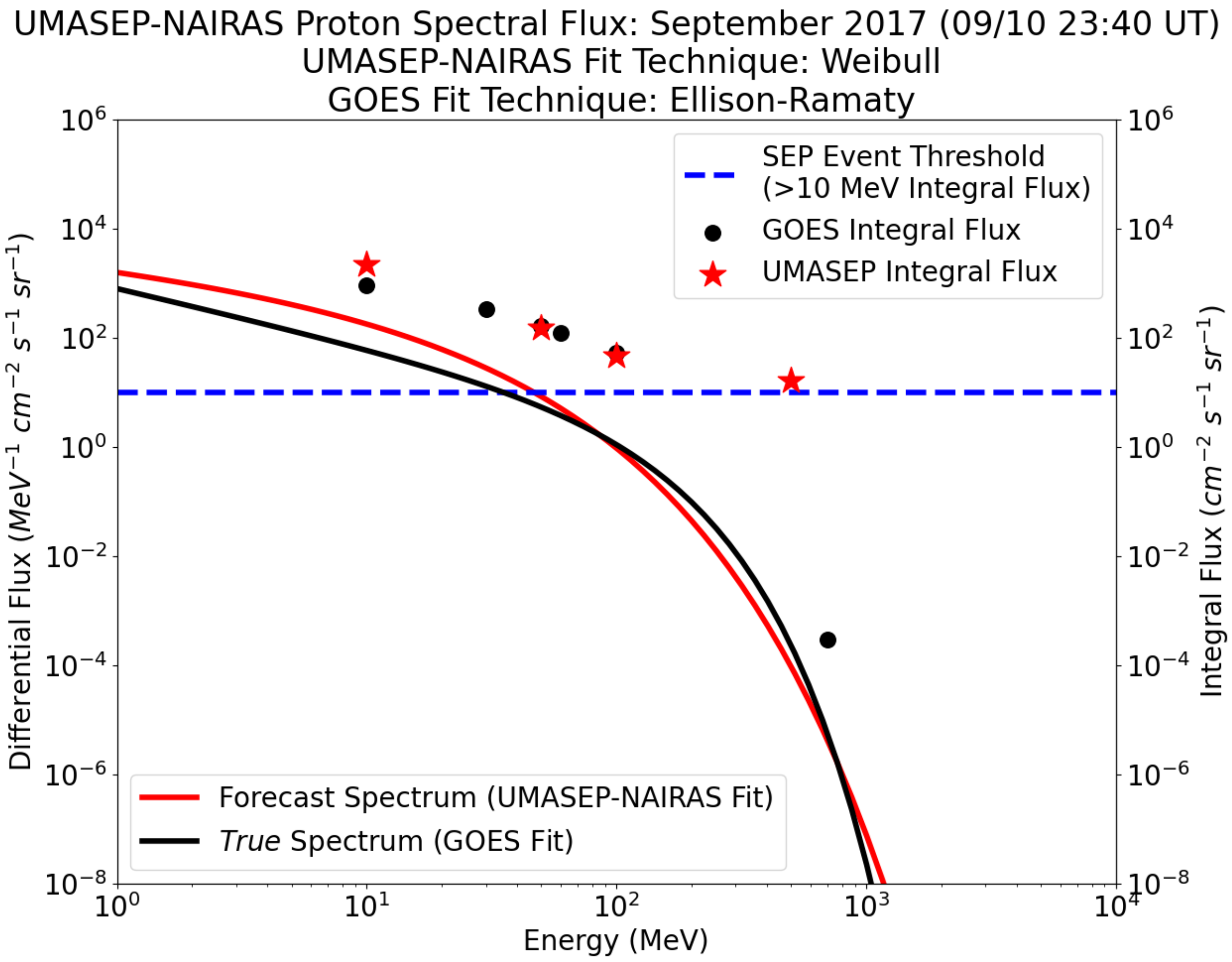




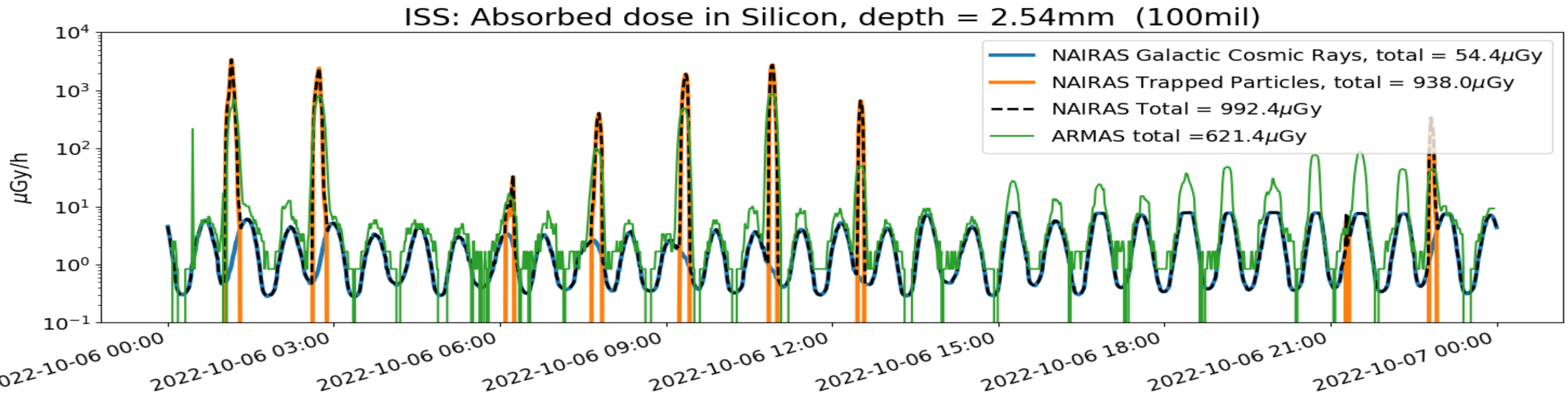
Other UMASEP Peak Integral Proton Flux Forecast Products: >50 MeV, >100 MeV, >500 MeV

UMASEP-NAIRAS SEP Forecast

7 hours after UMASEP >10 MeV integral proton flux forecast issue time

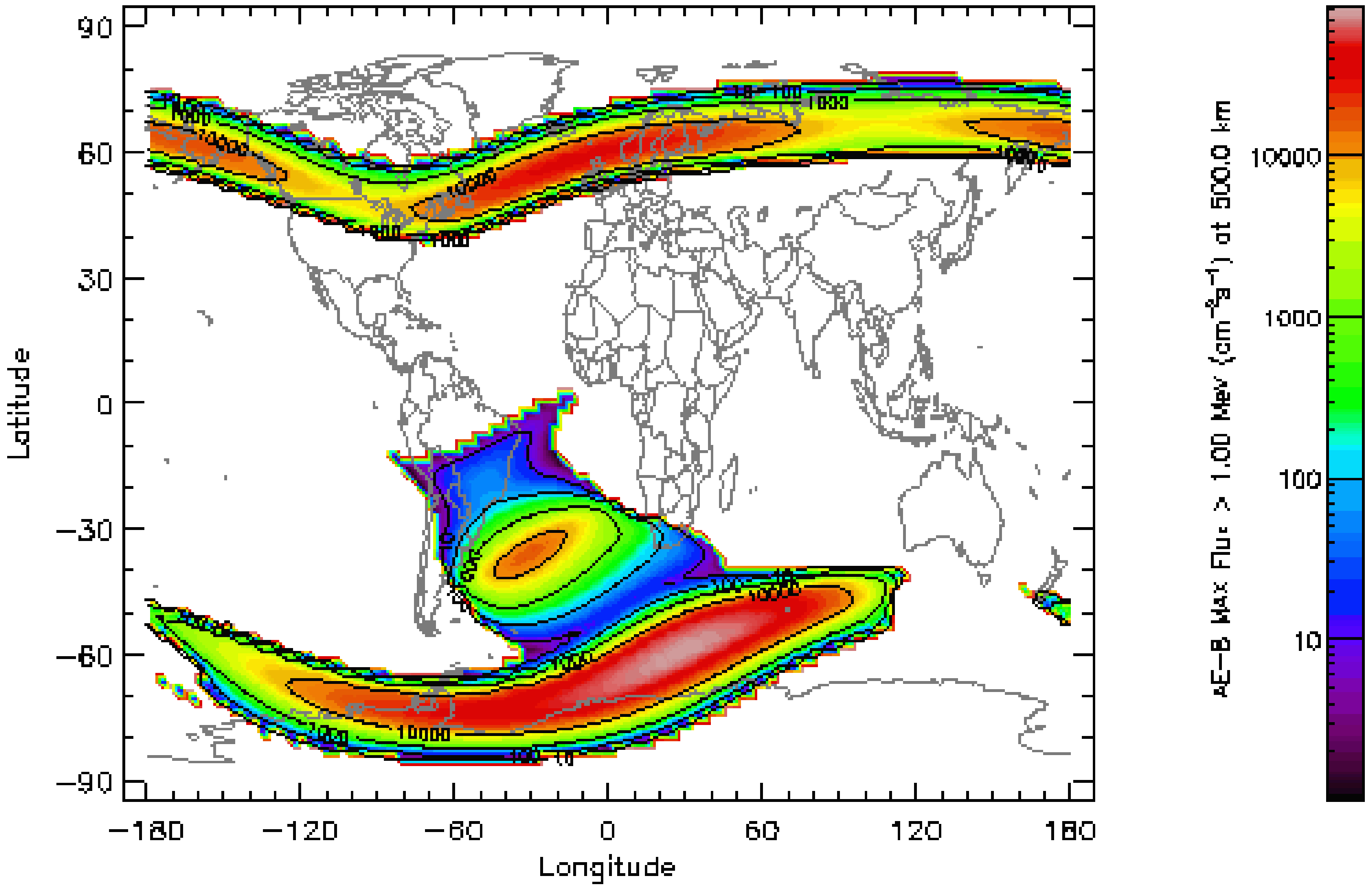


NAIRAS/ARMAS ISS Comparison (Oct 6, 2022)



- NAIRAS underestimates ARMAS within 30% for GCR, except sometimes at high-latitude …
- … NAIRAS underestimation of ARMAS at high-latitude due to outer-belt electrons
- NAIRAS overestimate ARMAS in SAA by factor 2
- NAIRAS overestimate ARMAS accumulated daily dose by 60%, which is consistent with the other 208 days of ARMAS data on ISS

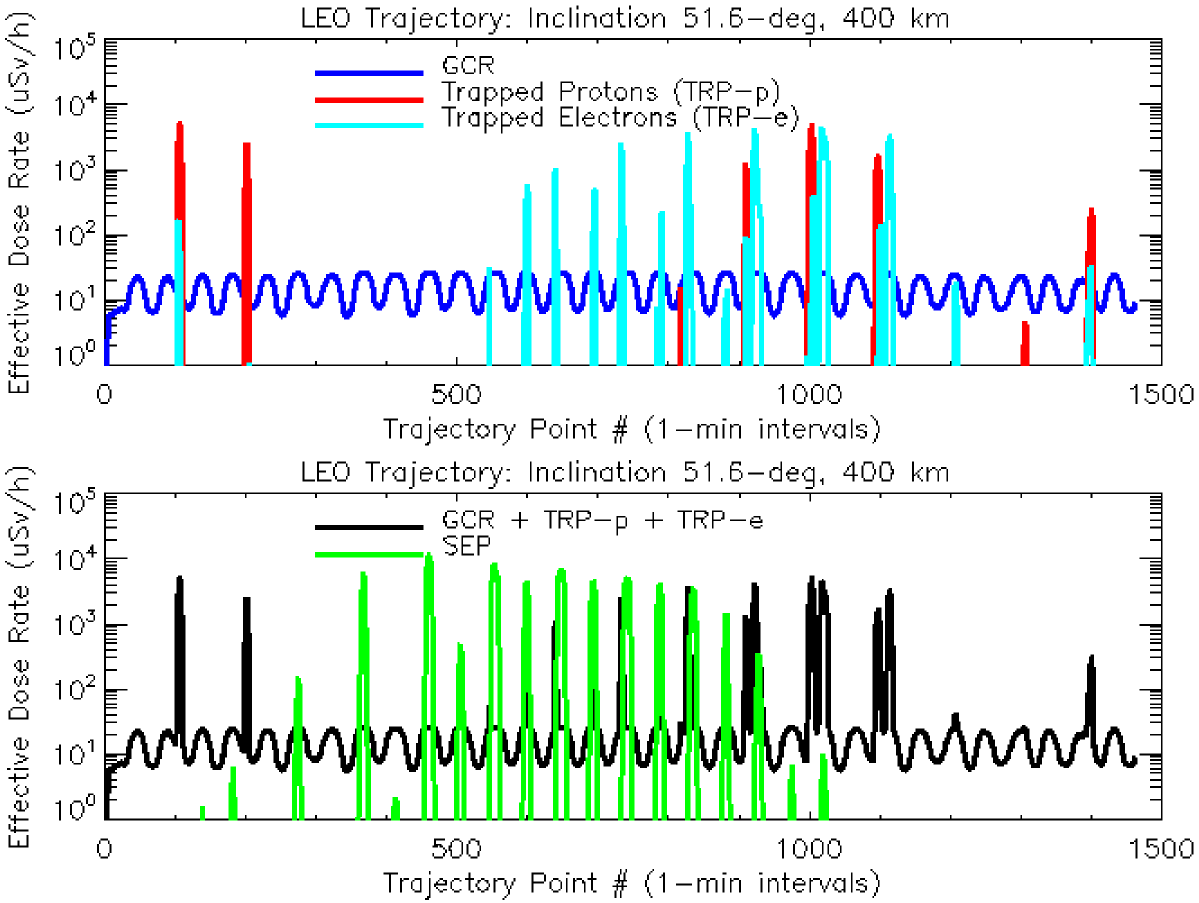
Trapped Electron Flux (AE8)



https://www.spenvis.oma.be/help/background/traprad/traprad.html

Trajectory Effective Dose (GLE 67)

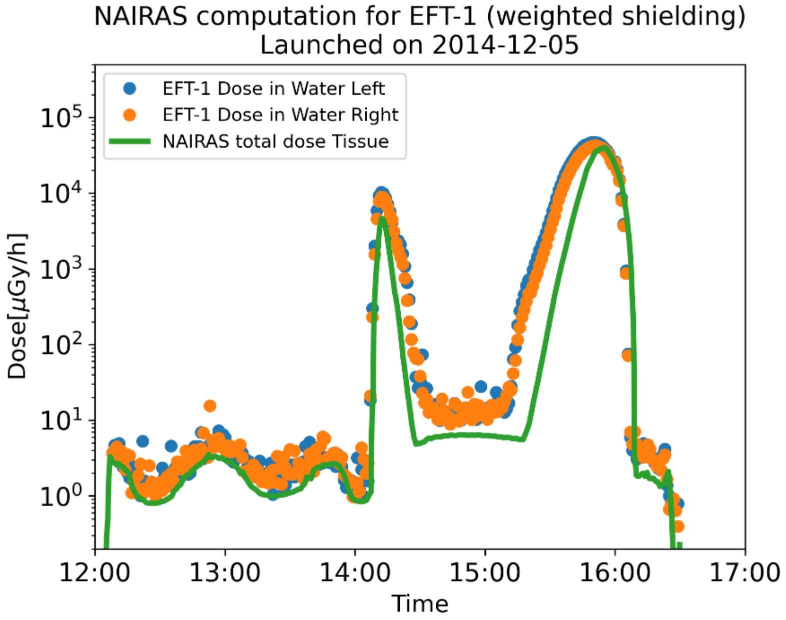
November 02 16:00 UT – November 03 16:00 UT

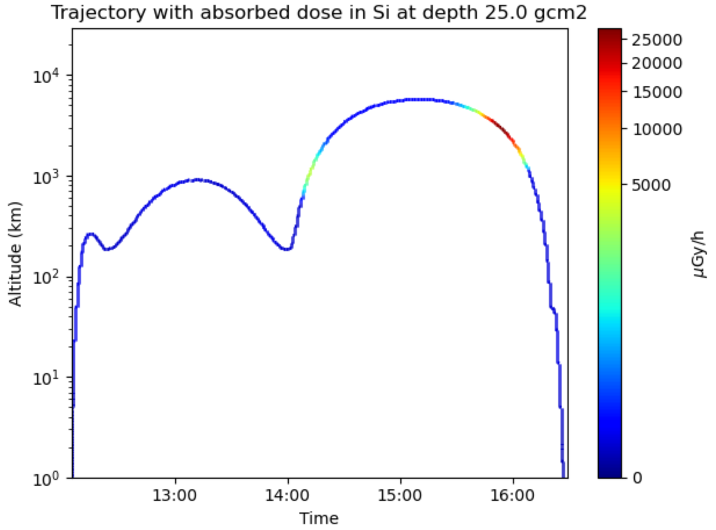


Al Shielding: 1 g/cm^2

NAIRAS/BIRD Comparison on NASA EFT-1 Flight

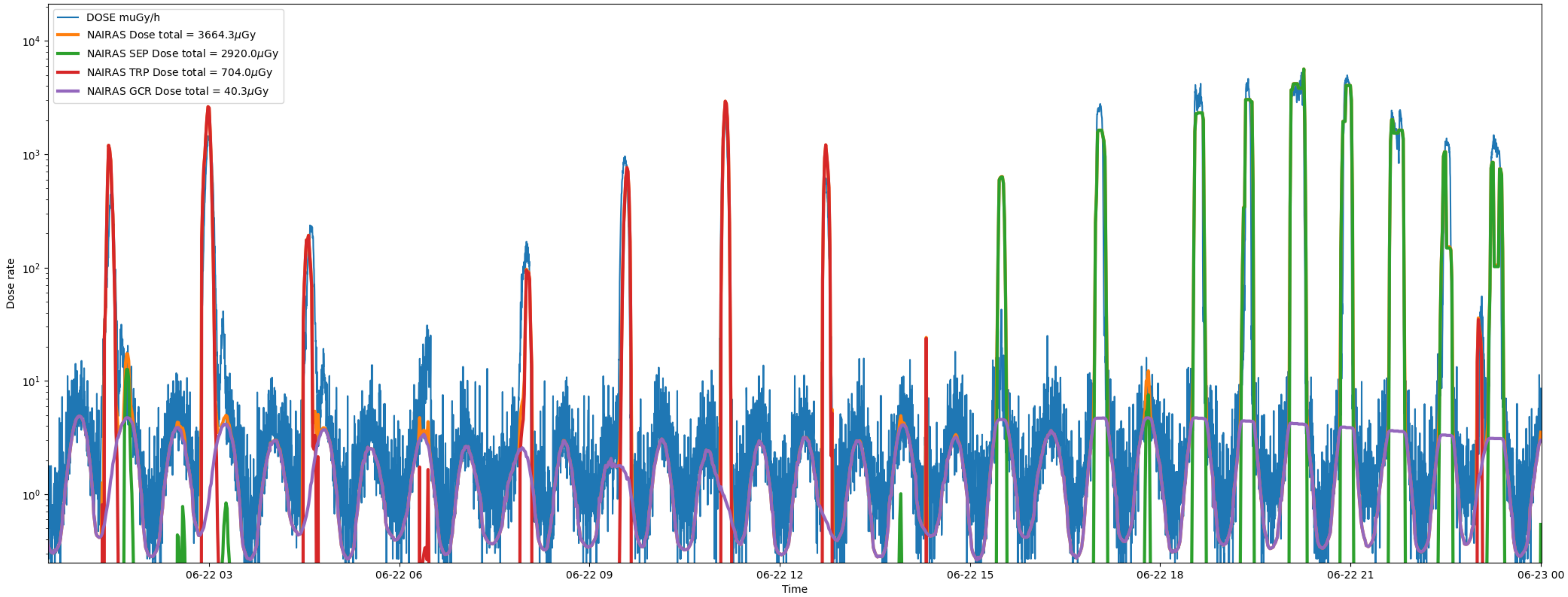
- **NASA Orion Exploration Flight Test-1 (EFT-1)**
  - Unmanned flight of NASA Orion Multi-Purpose Crew Vehicle (MPCV)
  - Orbital inclination: 28.6 degree
- **Battery-operated Independent Radiation Detector (BIRD)**
  - Two BIRD active semiconductor detectors (called Left/Right): Timepix technology
  - Data analysis algorithm converts dose in silicon to dose in water (proxy for tissue)
- **NAIRAS/BIRD Comparison**
  - NAIRAS underestimates BIRD by 60% in GCR region (before 14 UT) and TRP region (later than 14 UT)
  - BIRD overestimates total flight dose of other onboard dosimeter systems by 20%.
  - Considering BIRD biased by 20%, NAIRAS underestimates BIRD by 40%
  - NAIRAS uncertainty for GCR known to be within 30%





NAIRAS/Liulin ISS Comparison (June 2015 SEP)

Liulin dosimeter outside ISS on ESA EXPOSE-R2 Platform



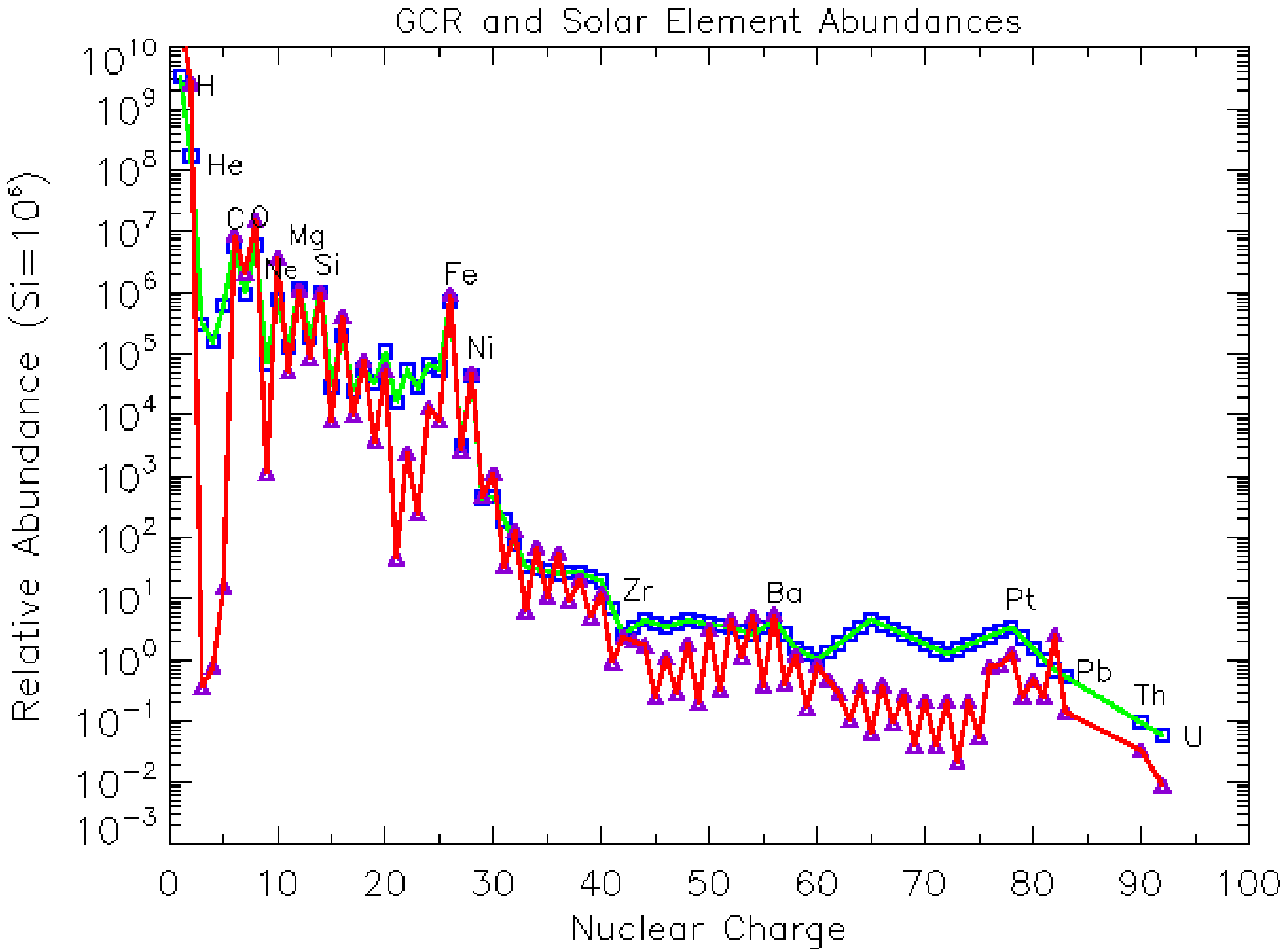
Al Shielding: 0.8 g/cm²

Summary and Conclusions

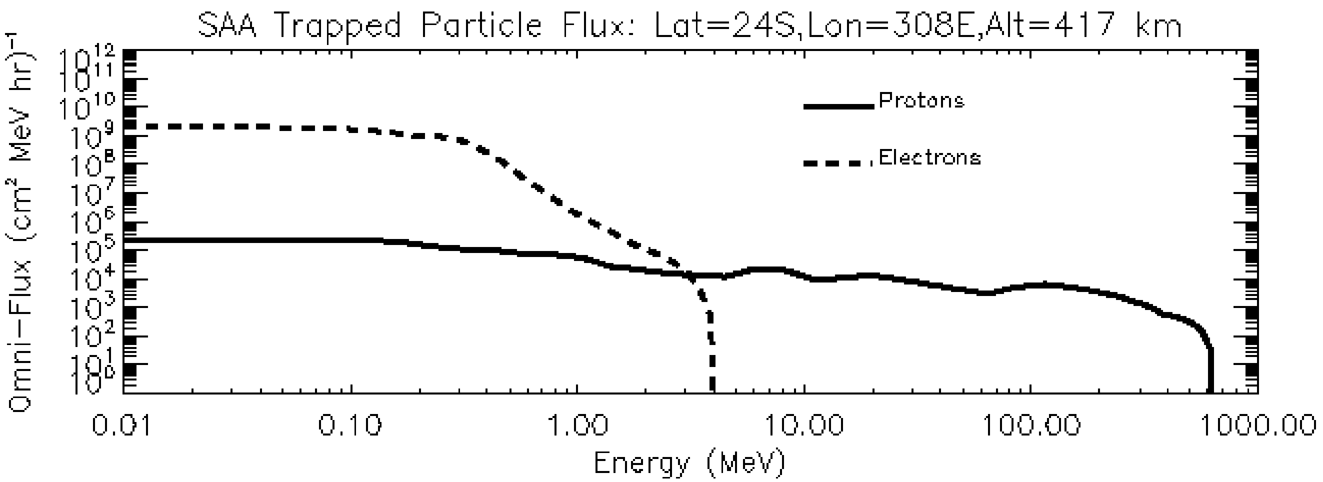
- **New NAIRAS Real-Time Aviation Radiation Dosimetric Products at 20 km**
- **New NAIRAS RoR Capability (publicly available since Feb 2023)**
    - Users can run the model for customized scenarios and perform scientific and engineering analysis of the atmospheric and space radiation environments
    - **Global dosimetric run option:** context and situational awareness
    - **Flight trajectory run option:** detailed human flight radiation exposure characterization, detailed comparisons with onboard dosimeters, provide inputs to radiation effects models to assess SEE in aircraft and spacecraft flight electronics
    - **Usage Metrics**: 400+ user jobs submitted so far in 2023
- **NAIRAS agrees with measurements to within 30% from 0-40 km**
- **NAIRAS comparisons with measurements in the space environment are encouraging (generally less than 60%)**
    - ISS low-Earth orbit (LEO)
    - NASA EFT-1 medium-Earth orbit (MEO)
    - NASA Artemis-1 cislunar orbit
- **Next Steps**
    - Outer-belt electrons (AE8 with solar modulation) available soon
    - Comprehensive validation studies: (1) Publish comparisons with 1000+ ARMAS aircraft flights, (2) Publish comparisons with RaD-X campaign measurements, and (3) 208 days of ARMAS-ISS data

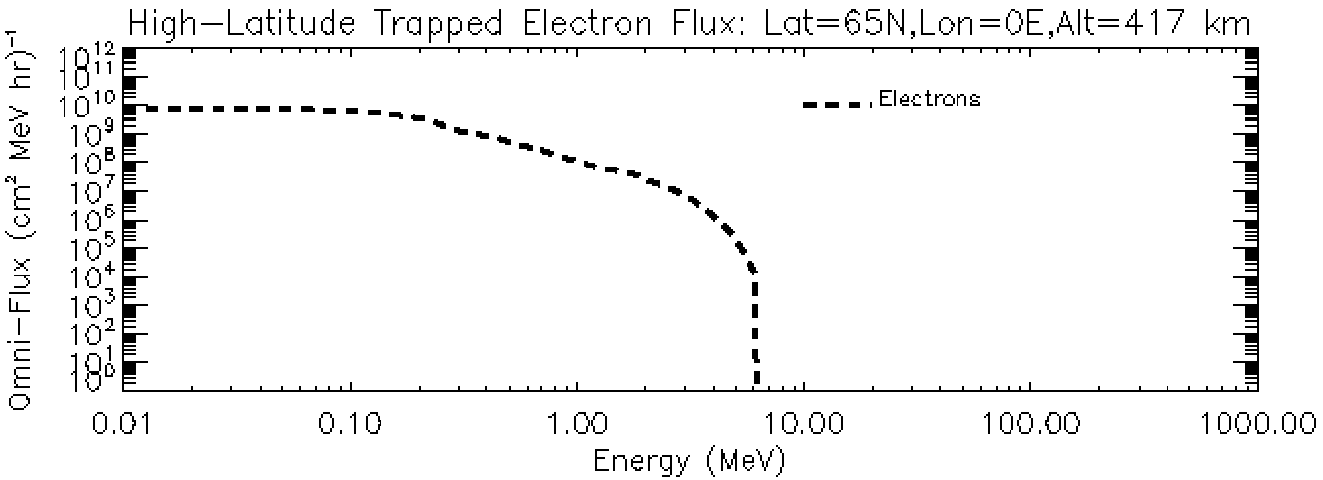
Backup Slides

SEP Heavy-Ion Model



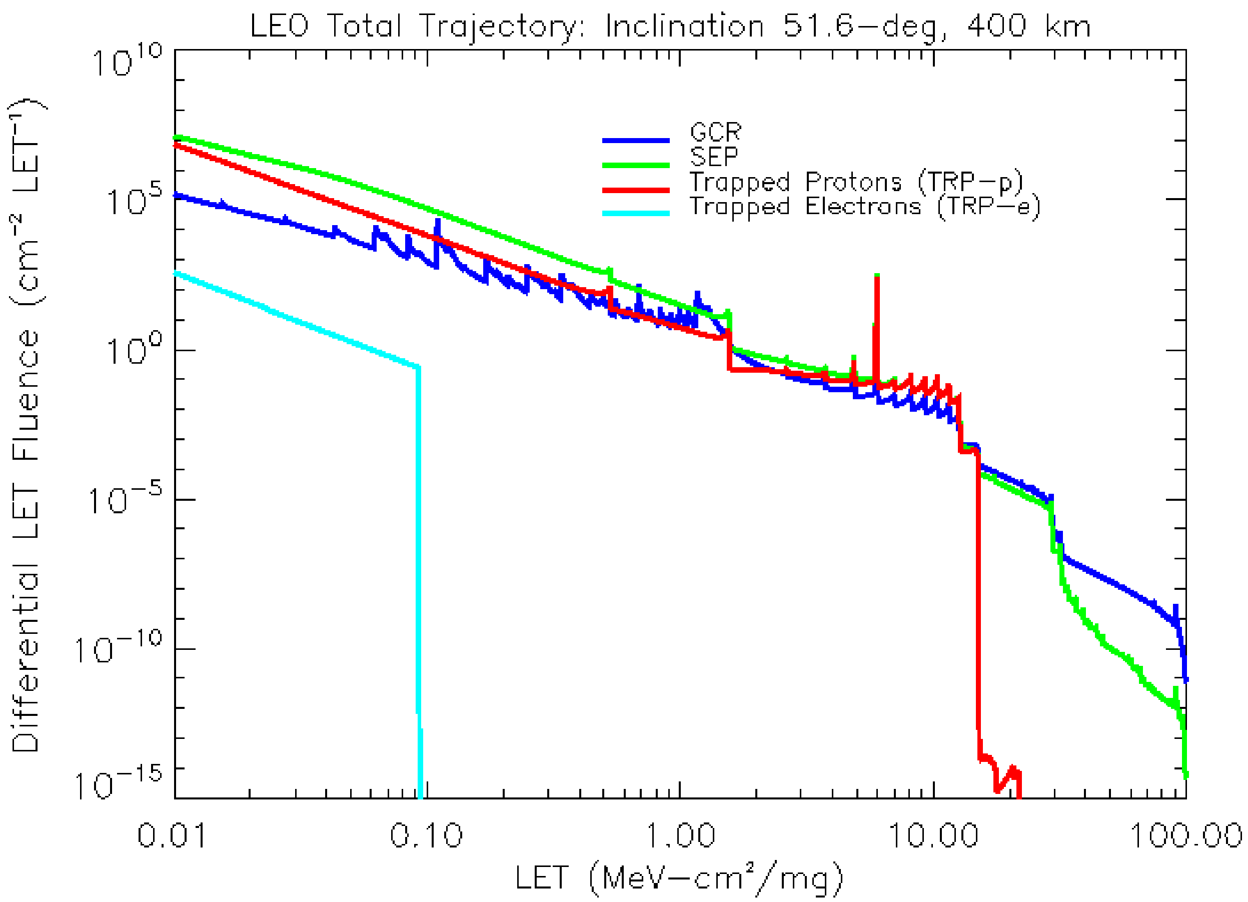
GEOFFB Trapped Particle Flux





Trajectory LET Spectra (GLE 67)

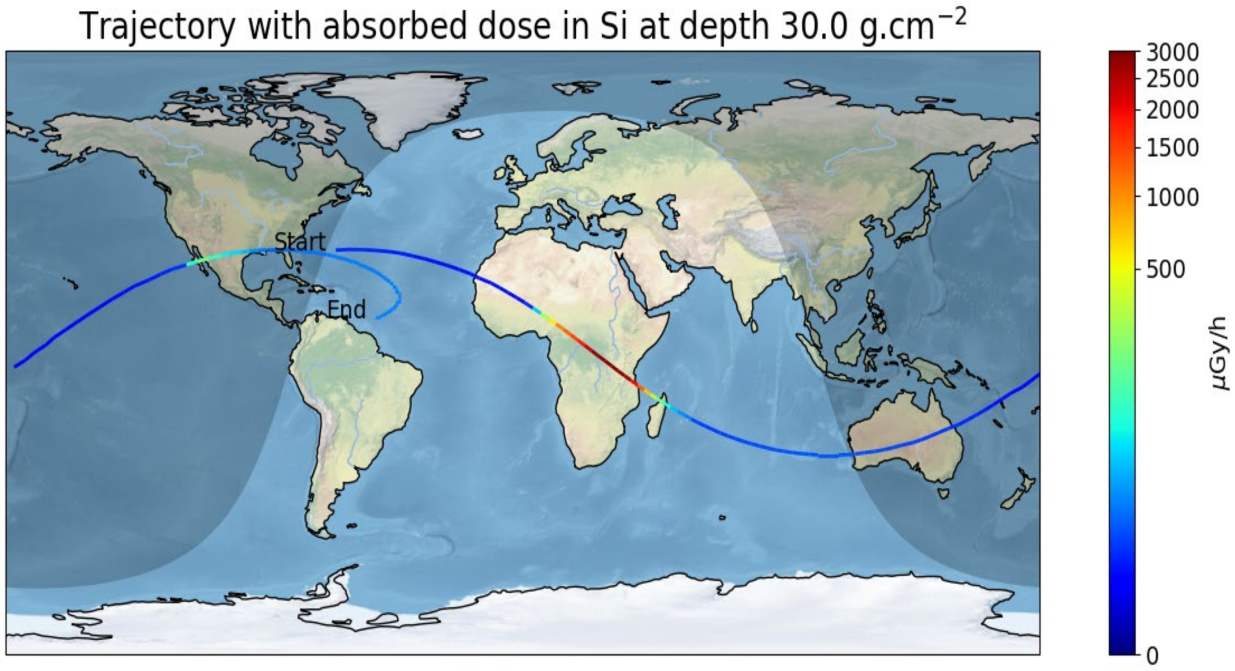
November 02 16:00 UT – November 03 16:00 UT

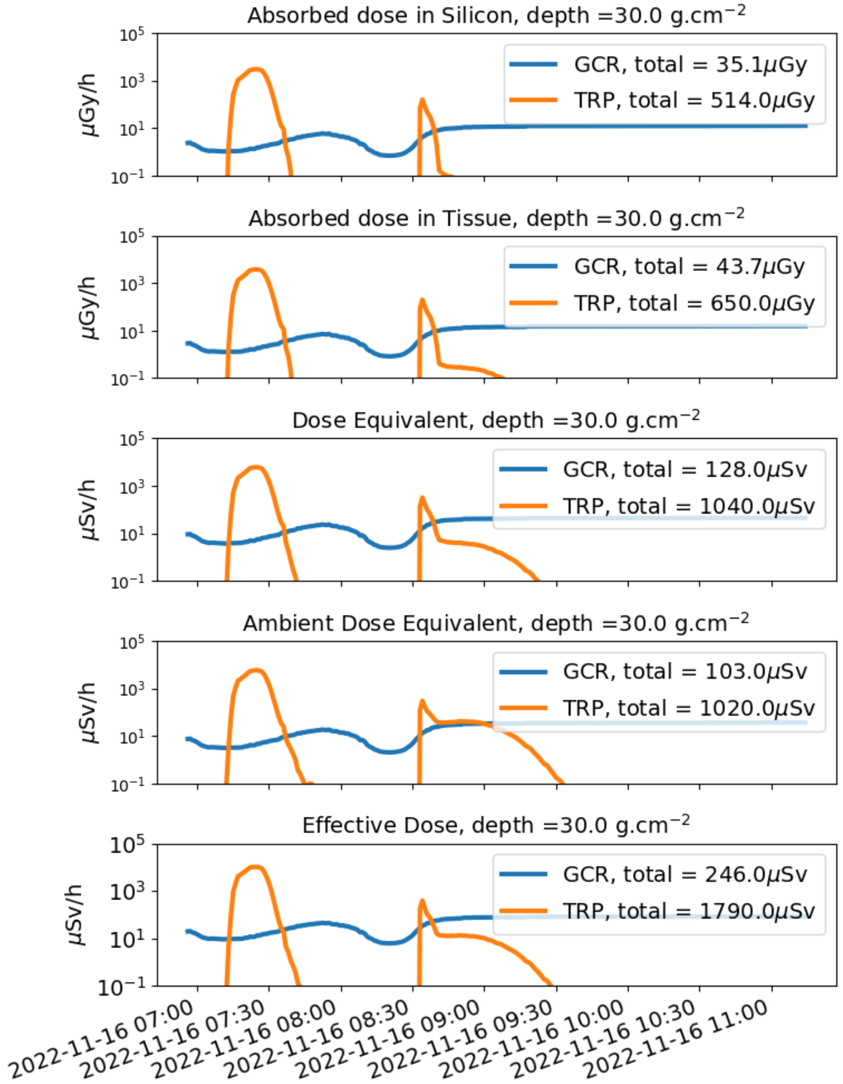


Al Shielding: 4 g/cm²

NAIRAS Dose: NASA Artemis-1 Mission

November 16, 2022





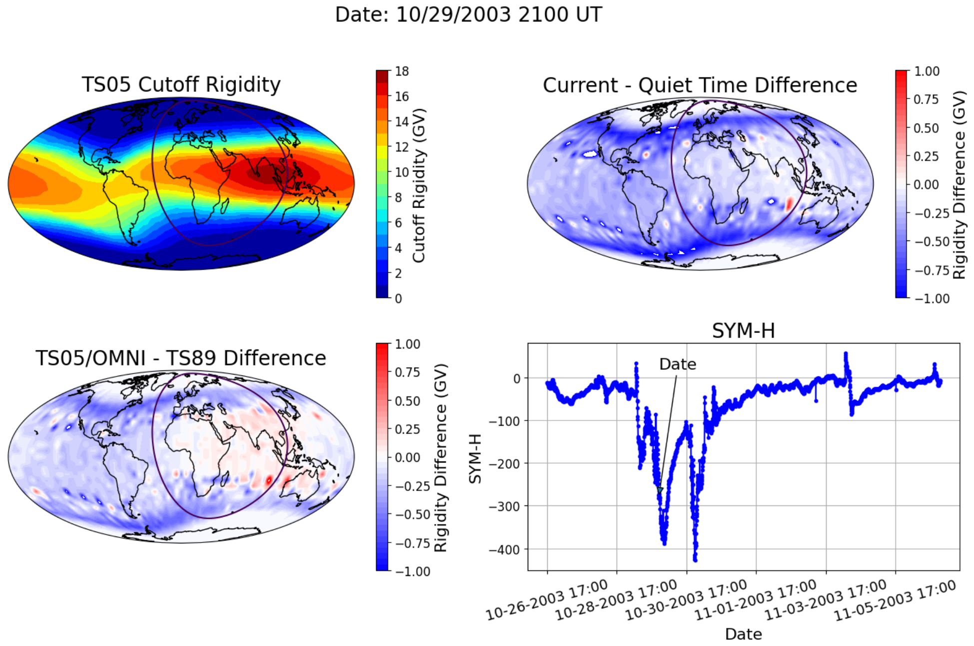
NAIRAS Free-Space Dose Rates (30 g/cm^2)

- Absorbed dose in silicon: 12-13 uGy/h
- Effective dose: 80 uSv/h

Geomagnetic Cutoff Rigidity Model

- **Based on CISM-Dartmouth model with TS05 magnetospheric B-field** (*Kress et al., 2010*)
- **Added multiple magnetospheric B-field selection capability**
    - **TS05** → parameterized by solar wind quantities, interplanetary magnetic field (IMF), SYM-H/Dst, and other derivative solar wind quantities
    - **T89** → parameterized by the planetary K-index (Kp)
- **The TS05 better represents magnetospheric responses to interplanetary disturbances**
    - but real-time solar wind parameters available from ACE/DSCOVR 1995+
- **Benefits of T89 option**
    - NAIRAS can simulate any historical solar-geomagnetic storm event
    - Extend/enhance validation capabilities
    - Provide initial step in forecasting cutoff via Kp-parameter forecast

Halloween 2003 Geomagnetic Storm



Top Right: Largest suppression of cutoff (~1 GV) (open-closed field boundary) occurs in dusk sector due to max build-up of partial ring current in TS05 (IMF Bz dependent)

Bottom Left: T89 doesn't well represent max cutoff suppression and cutoff in dusk sector